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Influence of Attentional Capture on Oculomotor Control

Jan Theeuwes
TNO Human Factors Research Institute

Arthur F. Kramer, Sowon Hahn, David E. Irwin, and Gregory J. Zelinsky
Beckman Institute and University of Illinois at Urbana-Champaign

Previous research has shown that when searching for a color singleton, top-down control cannot prevent attentional capture by an abrupt visual onset. The present research addressed whether a task-irrelevant abrupt onset would affect eye movement behavior when searching for a color singleton. Results show that in many instances the eye moved in the direction of the task-irrelevant abrupt onset. There was evidence that top-down control could neither entirely prevent attentional capture by visual onsets nor prevent the eye from starting to move in the direction of the onset. Results suggest parallel programming of 2 saccades: 1 voluntary goal-directed eye movement toward the color singleton target and 1 stimulus-driven eye movement reflexively elicited by the abrupt onset. A neurophysiologically plausible model that can account for the current findings is discussed.

Among the most fundamental issues in vision is the extent to which selection is controlled by the properties of the image or by the intentions, goals, and beliefs of the observer (for recent reviews, see Egeth & Yantis, 1997; Theeuwes, 1993, 1994a; Yantis, 1998). When an observer intentionally selects only those objects required for the task at hand, selection is said to occur in a voluntary, goal-directed manner. When specific properties present in the visual field determine selection independent of the observer's goals and beliefs, selection is said to occur in an involuntary, stimulus-driven manner.

There is ample evidence that salient display changes capture attention in an involuntary stimulus-driven manner (e.g., Breitmeyer & Ganz, 1976; Jonides, 1981; Müller & Rabbitt, 1989; Remington, Johnston, & Yantis, 1992; Theeuwes, 1991a, 1994a; Yantis & Jonides, 1984; however, see Folk, Remington, & Johnston, 1992). Jonides (1981) used peripheral cues with abrupt onsets that provided no predictive information about the likely target location. Even when participants were explicitly told to ignore these uninformative abrupt-onset cues, the results indicated that participants were unable to do so. Jonides concluded that abrupt-onset cues direct attention to their location even when participants deliberately attempt to ignore them. Recently, Remington et al. (1992) found even stronger evidence that abrupt onsets capture attention in an involuntary, stimulus-driven manner. In Jonides (1981), the cue indicated the likely target position at chance level. In Remington et al. (1992), however, the abrupt-onset cue never indicated the target location, and participants were explicitly told to ignore the abrupt onset. The results indicated that the condition in which the abrupt-onset cue indicated reliably the invalid location was slower than the condition in which none or all locations were cued, suggesting that attention was drawn to the abrupt onset even when participants knew it was irrelevant for the task.

Theeuwes (1994b) also found that irrelevant abrupt onsets captured attention in a stimulus-driven manner. Instead of asking participants to ignore the abrupt onset, in his experiments participants received the explicit instruction to search for a color singleton. In other words, the goal of the observer (i.e., top-down attentional set) was to find a color singleton (a gray circle among red circles). The results indicated that participants were much slower in those conditions in which an abrupt onset was presented, suggesting that attention was drawn involuntarily to the location of the abrupt onset. Theeuwes (1995) used the same paradigm and varied the time between the presentation of the to-be-searched-for color singleton and the appearance of the to-be-ignored singleton. The results indicated that when the color singleton and the abrupt onset were presented simultaneously, the interference caused by the irrelevant onset was the largest. With an increasing stimulus onset asynchrony (SOA) between the color singleton and abrupt onset (up to 150 ms), the extent to which the abrupt onset captured attention was reduced, suggesting that as soon as attention is well focused on the color singleton, abrupt onsets elsewhere in the visual field ceased to capture attention (see also Theeuwes, 1991a; Yantis & Jonides, 1990).

Even though there is a large body of evidence that abrupt onsets capture attention in an involuntary, bottom-up fashion (however, see Folk et al., 1992; Folk, Remington, & Wright, 1994), it is largely unknown whether such an event also

Jan Theeuwes, TNO Human Factors Research Institute, Soesterberg, the Netherlands; Arthur F. Kramer, Sowon Hahn, David E. Irwin, and Gregory J. Zelinsky, Beckman Institute and Department of Psychology, University of Illinois at Urbana-Champaign.

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Correspondence concerning this article should be addressed to Jan Theeuwes, who is now at the Department of Cognitive Psychology, Vrije Universiteit, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands. Electronic mail may be sent to j.theeuwes@psy.vu.nl.

triggers a subsequent eye movement. There is, however, substantial evidence that there is a close relationship between the oculomotor and attentional systems (e.g., Rizzolatti, Riggio, Dascola, & Umilta, 1987; Sheliga, Riggio, & Rizzolatti, 1994). For example, the *premotor hypothesis of attention* holds that attentional shifts to a stimulus are made on the basis of an eye movement program to a location (Rizzolatti et al., 1987). In this view, a shift of attention to a location is the result of programming a saccade to that location (however, see Klein, 1980; Klein & Pontefract, 1994). In cases in which only attention shifts, the "go" command to actually execute the saccade is inhibited.

Shepherd, Findley, and Hockey (1986) showed that manual reaction time (RT) to a target was shorter when the location of the target and the location to which a saccade had to be made coincided relative to conditions in which the target location and the location of the saccade were on opposite sides of the visual field. Similarly, Hoffman and Subramaniam (1995) asked participants to make a saccade to a specified location while also detecting a visual target presented just before the eye movement. Detection accuracy was highest when the location of the target coincided with the location of the saccade. Kowler, Anderson, Dosher, and Blaser (1995) combined a letter identification task with an eye movement task and found that performance was best when the saccade was directed at the to-be-identified letter. Deubel and Schneider (1996) had participants discriminate a letter in a string of other letters. Performance was best when the letter to be identified appeared at the same location to which a saccade had to be made. Discriminating nearby letters was at a near-chance level. In summary, these results indicate that there is an obligatory and selective coupling between saccade execution and visual attention to one common target object. Furthermore, when saccades are executed, attention precedes the eyes to the saccade target location. Typically, the eye will land at or near the position at which attention is directed. The researchers have investigated only the relationship between attention and the execution of *voluntary* goal-directed eye movements, however.

In the present research we addressed the issue of the extent to which visual selection (i.e., attention and eye movements) is controlled in a goal-directed or in a stimulus-driven manner. Similar to previous studies addressing the extent to which visual attention is controlled in a stimulus-driven or goal-directed manner (e.g., Theeuwes, 1991b, 1992, 1994b), in the current research goal-directed selection was pitted against stimulus-driven selection. In addition to examining the capture of attention as traditionally derived in terms of patterns of manual RTs and accuracy, we also examined capture of the eyes. The task we used was similar to that used by Theeuwes (1995), in which participants had the explicit instruction to search for a color singleton. In other words, participants had a top-down attentional set for a color singleton. At different SOAs after the presentation of the color singleton, a task-irrelevant to-be-ignored abrupt onset was presented somewhere in the visual field. Theeuwes (1995) had participants respond to the orientation of a line segment located inside the color singleton circle. In that study, it was ensured that the line segment inside the color singleton was so large that its orientation could be determined by directing spatial attention to that location. In the current research, we did just the opposite: We ensured that the letter presented inside the color singleton was so small that its identity could be revealed only after actually fixating the color singleton. In other words, the letter was so small that the high acuity of the fovea was necessary to resolve the identity of the letter. In the current paradigm, participants had the top-down goal to rapidly make a saccade to the color singleton and respond to the letter located inside the color singleton (see also Theeuwes, Kramer, Hahn, & Irwin, 1998).

The condition in which a to-be-ignored abrupt onset was presented somewhere in the visual field was compared with a control condition in which the additional circle was already present during the premask display. In this way we ensured that when the search display was presented, the number of circles present in the display was the same in the control and experimental conditions. The only difference between these conditions was that in the experimental condition the additional circle was presented with an abrupt onset, whereas in the control condition it was not.

In addition to measuring manual RT to examine whether the appearance of the onset slowed responding, we also measured the actual path of the eye through visual space. The participants' goal was to fixate the color singleton. The question addressed was whether abrupt onsets would capture the participants' eyes. If so, this would indicate bottom-up control of selection at the oculomotor level. Recording eye movements to address the issue of top-down and bottom-up control of selection provides information that cannot be obtained with conventional RT measures. Instead of just showing an increase in manual RT when the abrupt onset is present, these measures can actually show whether the increase in RT is caused by the fact that the eye went to the location of the irrelevant onset before the location of the target.

Experiment 1

Method

Participants. Eight participants (aged 18–28 years) served as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no color vision defects.

Apparatus. A Gateway Pentium 133-MHz computer with a 19-in. (48.26 cm) super video graphics array color monitor controlled the timing of the events, generated stimuli, and recorded RTs. The forward slash key and the *z* key of the computer keyboard were used as response buttons. Eye movements were recorded with an eyelink tracker (SR Research, Toronto, Ontario, Canada) with a 250-Hz temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the pupil center and pupil size of both eyes. An infrared head motion tracking system tracked head motion. Even though head motion was measured, in the experiment the head was stabilized with a chin rest. Three thresholds were used for saccade detection: movement distance, velocity, and acceleration. An eye movement was considered a saccade either when the movement distance exceeded 0.2° and velocity exceeded 30°/s, or when the movement

distance exceeded 0.2° and the acceleration exceeded 8,000°/s². During the experiment, eye position was monitored on-line. On each trial, during the fixation display when participants fixated the center fixation dot, the eye position was automatically recalibrated to the center position to optimize the reliability of the eye movement measurements. After participants were well fixated on the center fixation dot, they pressed a key to initiate a trial. Each participant was tested in a sound-attenuated, normally lit room, with his or her head resting on a chin rest. The monitor was located at eye level, 55 cm from the chin rest.

Stimuli. The participants performed a visual search task in which they searched for a color singleton circle and responded to the element located inside the color singleton. Participants viewed displays containing six equispaced gray circles (3.7° in diameter), with each containing a small gray figure eight premask (0.4° × 0.2°) presented on an imaginary circle with a radius of 12.6°. The six circles always appeared at clock positions 1, 3, 5, 7, 9, and 11 on the large imaginary circle. After 1,000 ms all the gray circles but one changed to red. Simultaneously with the color change, line segments were removed from each of the figure eight premasks revealing target and distractor letters and the center fixation point changed from a "star" to a "plus" sign (see Figure 1). The letters inside the red circles were distractor letters randomly sampled without replacement from the set S, H, E, P, F, and U; the letter inside the single gray circle was the target and consisted of either a C or a reversed C, with the orientation of the letter determining the response (participants pressed the forward slash key for a C and the *z* key for a reversed C). Because the letters were small and were

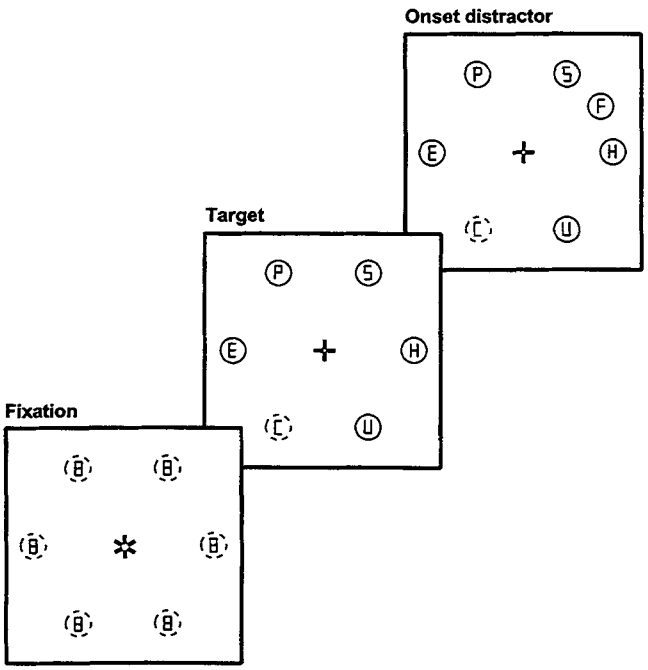

Figure 1. Sequence of events during a trial. After a 1,000-ms fixation, all gray circles (dashed lines) except one changed to red (solid lines); at the same time the small premask inside the circles changed to letters. Depending on the condition an additional red onset distractor circle was added to the display with either a 0-, 80-, or 150-ms stimulus onset asynchrony. Participants had to make an eye movement to the gray circle (color singleton) and respond to the identity of the small letter located inside the gray circle. The stimuli are not drawn to scale.

located 12.6° from the fovea, participants had to make a saccade to the gray circle (the color singleton) to identify the target letter. The red and gray circles were matched for luminance (24 cd/m²).

In addition to the six circles, in the onset condition, we added an additional red circle (identical to the other five red circles) with a distractor letter inside to the display either simultaneously (at the 0-ms SOA) or slightly later than the search display (at SOAs of 80 or 150 ms). The additional red circle appeared with an abrupt onset at one of four possible locations (at either the 2, 4, 8, or 10 o'clock position). These four possible locations of where the onset could appear corresponded to three possible angular distances from the gray target circle. On the imaginary circle with the fixation dot as its center, the abrupt onset could be presented next to the target describing an angle between target and distractor of 30° of arc, 3 o'clock positions away from the target describing an angle of 90° of arc, or almost opposite the target describing an angle of 150° of arc. In euclidian distances, these distances correspond to 6.4°, 19.4°, and 25.4° of visual angle, respectively. The stimulus field remained present until a response was made. Figure 1 shows the sequence of events in each trials.

Design. Participants were presented with two conditions: (a) a control condition in which the additional circle was already present in the display at the beginning of the premask (i.e., instead of adding the additional circle with an abrupt onset to the display, it was presented along with the other six circles) and (b) an abrupt-onset condition, in which an additional circle was added to the display with either 0-, 80-, or 150-ms SOA at any of the four possible locations. In total, each participant performed 192 control and 576 experimental trials. In the control condition, each participant had a total of 48 trials for each of the four distractor locations. In the experimental condition, each participant performed 48 trials for each SOA–distractor location condition. Distractor location and SOAs were randomized within blocks of trials. Experimental and control conditions were run in separate blocks of trials counterbalanced across subjects. In half the trials, the target letter was a C; in the other half, it was a reversed C, randomized within blocks.

Procedure. Participants served in two 1-hr sessions consisting of nine blocks of 48 trials each. Each session started with a practice block of 48 trials. Before the start of the experiment participants were instructed to search for the uniquely colored gray circle and to respond to the letter located inside it. Participants were instructed to press the appropriate response keys with their index fingers that were resting on the slash and *z* keys. It was explained that participants had to make a speeded eye movement to the odd-colored circle to identify the letter. Participants were told that they could begin to move their eyes as soon as they detected either the color change or the change of the fixation point. Participants were instructed to respond as fast as possible and to keep their eyes on the fixation point until the display changed. After responding participants refixated the fixation dot located in the center of the monitor.

Before the start of the experiment, the head band of the eyelink tracker with the infrared light source and camera were strapped tightly on the participant's head. A chin rest was used to stabilize the head. Participants were asked not to make any (large) head movements. The infrared sources and cameras were adjusted until there was a clear corneal reflection in both eyes. To calibrate the Eyelink system, participants had to fixate nine calibration targets (onsets) that were presented in a 3 × 3 grid in a random order across the monitor. As soon as a point was fixated, the next target came on. After calibration, the experiment started with a block of practice trials.

Results

Discarded data. For various reasons the data from some trials were discarded. Because of technical problems 2.9% of the trials were discarded. When participants were not well fixated on the center fixation dot at the beginning of the trial (e.g., making anticipatory eye movements), we discarded the trial. This led to a loss of about 8.0% of the trials. Those trials on which participants made errors (e.g., pressing the wrong response key) were also excluded from all analyses (a total of 1.3%). Because the error rates were low, we did not analyze error scores any further. In total, 12.2% of the trials were discarded and not analyzed further.

Manual RT. The first question addressed was whether the abrupt onset caused a distraction effect. To answer this question, we analyzed manual RT, that is, the time it took participants to press one of the response keys. The data for the control and onset distractor conditions were subjected to separate analyses of variance (ANOVAs). The onset condition with SOA (0, 80, or 150 ms) and distance from the target (30°, 90°, and 150° target–distractor distance) as factors showed only a main effect of SOA, $F(2, 14) = 6.8, p < .001$. As is clear from Figure 2, the distracting effect of the onset diminished when SOA was increased, suggesting that the onset caused less distraction when it appeared somewhat later than the color singleton. This finding is consistent with one by Theeuwes (1995).

In the control condition, in which the additional circle was presented along with the premask, RT was affected by the distance between the target and the additional circle $F(2, 14) = 11.0$, $p < .01$. Additional planned comparisons ($ps < .05$) indicated that when the additional circle was close to the target (at 30°), RT was significantly longer than when it was presented somewhat farther away (at 90°). In addition, when the additional circle was presented completely on the other side of the visual field (at 150° from the target) RT was shorter than when it was presented somewhat closer to the target (at 90°). These findings suggest that the mere presence of a circle close to the target singleton slowed down manual responding, possibly because the presence of a nearby circle may require the programming of a more precise eye movement (e.g., Bouma, 1978) or because attentional filtering costs increase when distractors are located close to targets (Treisman, Kahneman, & Burkell, 1983). Obviously, because it takes longer for the eye to get to the target singleton when another circle is close to the target, manual RT increases as well.

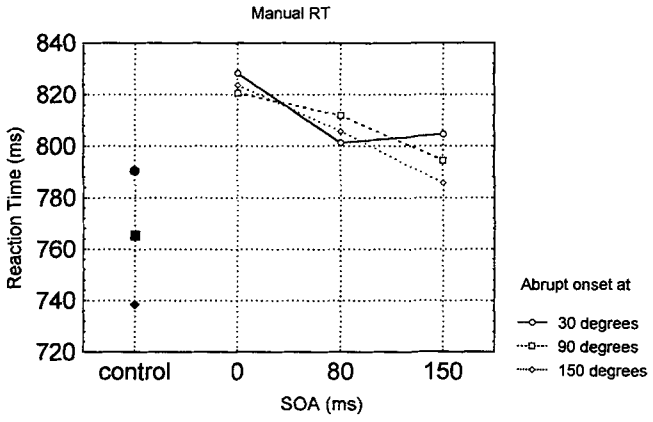

Figure 2. Manual mean reaction time (RT; in milliseconds) for the control and onset distractor conditions as a function of stimulus onset asynchrony (SOA) for each target–onset distractor separation.

For each distance between the target and distractor, the distracting effect of the onset was compared with its respective control. Planned comparisons showed that when the distractor was presented 30° from the target, there was a reliable distracting effect at the 0-ms SOA ($p < .01$). At the 30°, 80- and 150-ms SOAs, the distracting effects were not reliable, possibly because responding was relatively slow in the 30° control condition (see the earlier arguments). However, when the onset was located at 90° and 150° from the target, there was a reliable distracting effect at all three SOAs ($ps < .05$). These results indicate that in most cases the presentation of an abrupt onset slows down manual RT over and above any slowing caused by the mere presence of the no-onset circle (the control condition).

Together, these results suggest that even though the abrupt onset was irrelevant for the task, it caused a reliable distraction effect. Consistent with earlier results (e.g., Theeuwes, 1994b), these findings suggest that abrupt onset captured attention.

Saccade latencies in the control condition. An analysis of saccade latency in the control condition (i.e., the time it took the eye to start moving out of the center area after the color singleton target was revealed) suggested that the mere presence of a nearby circle indeed forced the programming of a more precise saccade. Planned comparisons ($p < .01$) showed that in the control condition, when the additional circle was located close to the target (at 30°), it took significantly more time for the eye to start moving than when the additional circle was located farther away (241 ms when the circle was located at 30° versus 228 ms located at 90° and 226 located at 150°). Note, however, that the increase in saccade latency (about 16 ms) and therefore the more precise programming of a saccade could not account for all the manual RT costs associated with the presence of an additional circle (the manual RT difference between a circle at 150° vs. 30° was about 50 ms). Therefore, it is plausible that in addition to the more precise programming of a saccade, there are also attentional filtering costs when a distractor is close to a target. For example, in Theeuwes's (1995) study, in which participants were required to shift attention instead of eye movements to a target location, a nearby no-onset circle caused an RT increase of about 20 ms. Obviously, because participants did not make any eye movement, these costs were not attributed to precise programming of saccades but instead to attentional "filtering costs" as described by Treisman et al. (1983).

Scan paths. The next question we addressed was whether the appearance of the abrupt onset also captured the eyes. In other words, would the appearance of the abrupt onset influence the trajectory of the eyes? Figure 3 shows the eye movement pattern at the 0-ms SOA collapsed over partici-

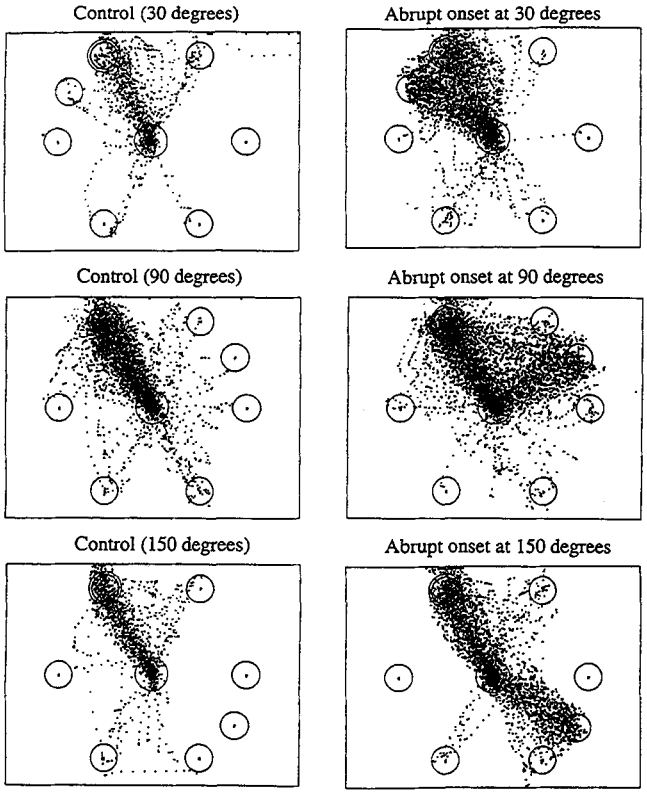

Figure 3. Eye movement behavior in the condition in which an abrupt onset was presented simultaneously with the target (0-ms stimulus onset asynchrony). The results are collapsed over all 8 participants and normalized with respect to the position of target and onset. Sample points (every 4 ms) were taken only from the first saccade. *Left panels:* Eye movement behavior in the control condition in which no abrupt onset was presented. *Right panels:* Eye movement behavior in the condition in which an abrupt onset was presented simultaneously with the singleton target, either close to the singleton target (at 30° of arc corresponding to a distance of 6.4° of visual angle, see top right panel), somewhat farther away from the singleton target (at 90° of arc corresponding to a distance of 19.4° of visual angle, see middle right panel), or at a side of the visual field opposite to that of the target singleton (at 150° of arc corresponding to a distance of 25.4° of visual angle, see bottom right panel).

pants, normalized with respect to the position of the singleton target for each distance between target and distractor. In this figure, only the first saccades are shown (corrective saccades are not displayed). As is clear, in the control condition in which no abrupt onset was present, the eyes often went directly in the direction of the location of the target. However, when an abrupt onset was presented at any of the locations within the display, the eyes tended to go in the direction of the location of the abrupt onset. Note that this also occurred for the condition in which the abrupt onset appeared on the side of the visual field completely opposite of that of the target.

To quantify the effects of the onset on the eye trajectory, we calculated the maximum angle of deviation of the eye from a linear path between the fixation dot and the target. Positive values indicated that the eye started moving in the direction of the onset, and negative values indicated that the eye started moving in a direction away from the onset. Figure 4 shows the distributions of this measure for the control and the 0- and 80-ms SOA conditions. As noted earlier in the control condition, the eyes went directly to the target: The majority of eye movements were within −20° to 20° of angular deviation from the target.

At the 0-ms SOA, however, it was clear that in a large proportion of trials, the eye started to move in the direction of the onset element. For a target–distractor separation of 30°, this was not easily seen because the onset was so close to the target, making it hard to determine which eye movements went to the target and which went to the distractor. However, at 90° and 150°, it was clear that in a large proportion of the trials, the eye went in the direction of the onset. We determined the number of trials in which the eye movements first went in the direction of the onset for both the experimental (i.e., an onset presented with a 0-, 90-, or 150-ms SOA) and control (i.e., no-onset distractor circle) conditions for the 90° and 150° target–distractor condition. Eye movements toward the onset had to have an angular deviation larger than 45° or smaller than −45° for the 90° separation and larger than 90° and smaller than −90° for the 150° separation. Relative to the control condition in which no onset was present, the proportion of trials on which the eye movements first went to the onset was significantly larger in the 0-ms SOA condition, $F(1, 7) = 22.9, p < .01$. At the 80-ms SOA, there was a trend that relative to the control condition, more eye movements first went in the direction of the onset, $F(1, 7) = 5.00, p = .06$. In the 150-ms SOA condition, the proportion of trials in the direction of the onset was the same as in the control condition, suggesting that in this condition the onset came too late to elicit an eye movement to the onset. Overall, the effect of distance between target and distractor (90° vs. 150°) was reliable, $F(1, 7) = 11.7, p < .05$. Figure 5 shows these results.

Saccade latencies for saccades toward and away from the target. The results indicate that there are two types of eye movements: those that went in the direction of the target and those that went in the direction of the abrupt onset. To determine whether there would be a difference in saccade latencies between these two types of eye movements, we analyzed the saccade latencies for the 0-ms SOA (this was the SOA in which many initial saccades went to the onset) for the 90° and 150° target–distractor separation. Saccades toward the target had to fall within a −20° and 20° of angular deviation from the target. Eye movements toward the onset had to have an angular deviation larger than 45° or smaller than −45° for the 90° separation and larger than 90° and smaller than −90° for the 150° separation. We did not include the separation of 30° between target and distractor in this analysis because it would not allow us to easily distinguish eye movements toward the target from those toward the onset distractor. An ANOVA on saccade latency with eye movement direction (toward target vs. toward onset) and distance (90°–150°) as factors showed a main effect of eye movement direction, $F(1, 7) = 9.6, p < .05$. When the eyes went in the direction of the target, its latency

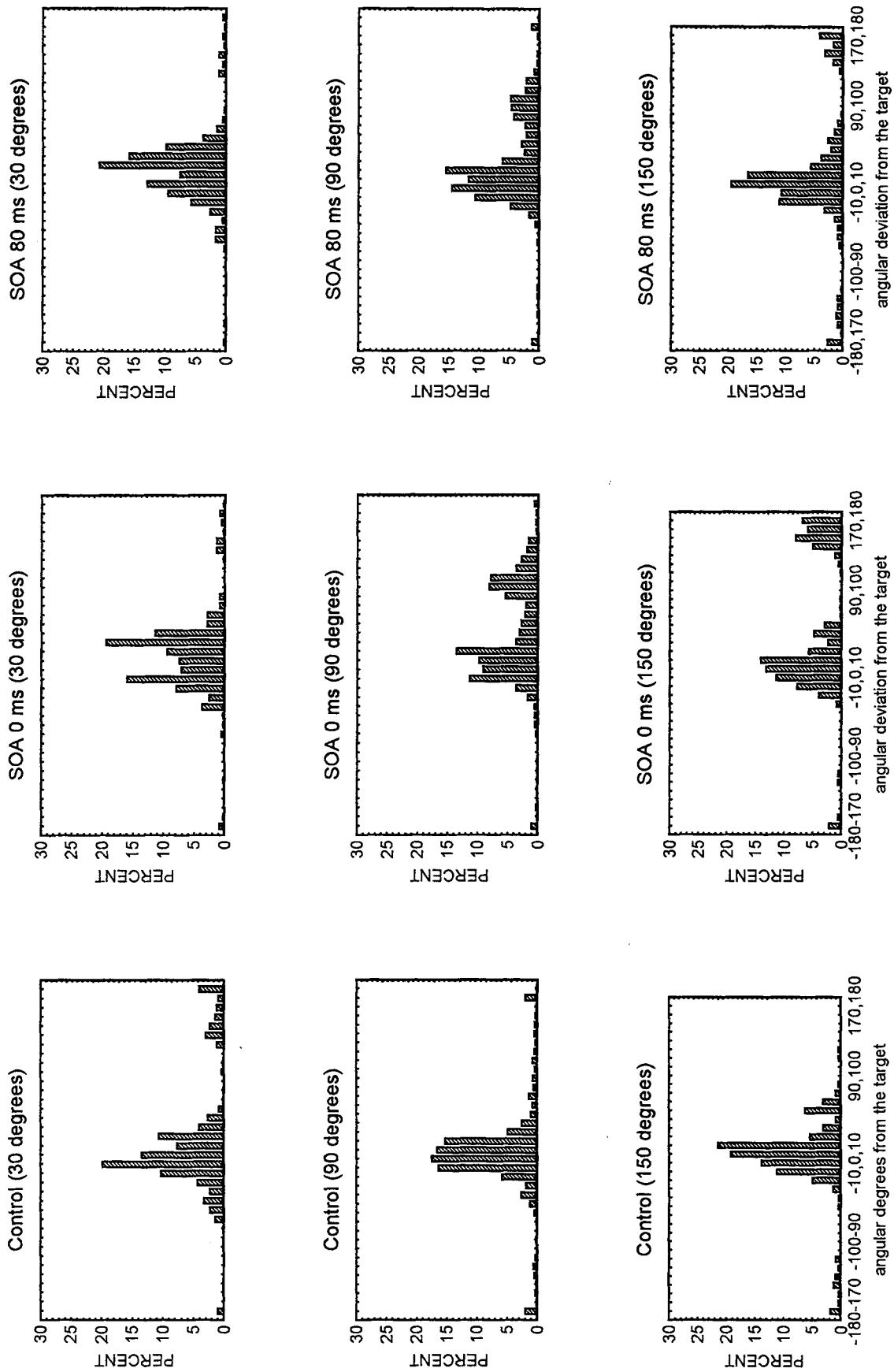

Figure 4. The effect of the appearance of the abrupt onset on the scan path of the eye. Shown is the maximum angle deviation of the eye from a linear path between the fixation and the target object (in degrees of angle; positive values indicate that the eye moved in the direction of the onset; negative values indicate that the eye went in the opposite direction). Sample points were taken only from the first saccade and collapsed across subjects. SOA = stimulus onset asynchrony.

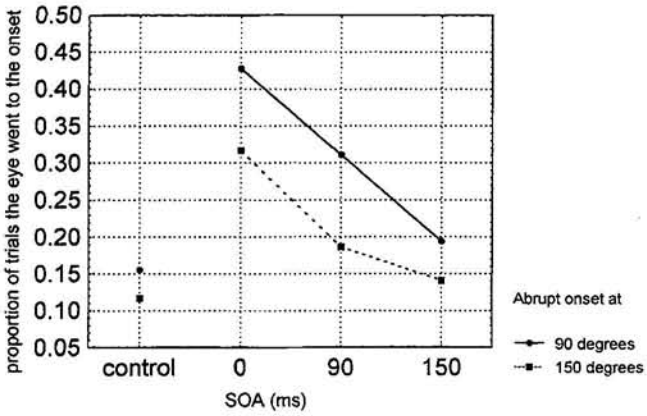

Figure 5. The proportion of trials the eyes first went in the direction of the onset for the control condition (no-onset distractor) and for the condition in which a distractor circle was added to the display with either the 0-, 80-, or 150-ms stimulus onset asynchrony (SOA).

was significantly slower than when the eye went in the direction of the onset (237 ms when the eye went to the target vs. 213 ms when the eye went to the onset).

Fixation durations after the first saccade. The data indicate that at the 0-ms SOA, the eye started moving in the direction of the onset in about 30%–40% of the trials. We analyzed the fixation durations after the first saccade for those saccades that went in the direction of the onset. For this analysis we used only the 90° and 150° target–distractor separation because these separations made it possible to distinguish eye movements toward the onset from those toward the target. In the analysis only eye movements that had an angular deviation of more than 45° from the target were used. Figure 6 shows the results. Note that 90% of the fixation durations were less than 150 ms, even though a complete change in the direction of the eye movement was required to redirect the eyes in the direction of the target. Because these fixation durations are too brief to allow the programming of a new eye movement (which typically takes 150–250 ms; see Findley, 1997; Salthouse & Ellis, 1980), the results suggest that at some point two eye movements were programmed in parallel (e.g., Becker & Juergens, 1979; Henderson & Ferreira, 1990). These findings suggest that the eye movement toward the singleton target is rapidly initiated after a brief fixation along the path between the fixation dot and the onset.

RTs for trials in which the eyes went to the target. An important question was whether the long manual RT at the 0-ms SOA condition (see Figure 2) was largely due to the fact that the eyes moved initially to the onset distractor on a large proportion of the trials. To answer this question, we separately analyzed those trials in which the eyes went directly to the target. Because it was impossible to separate trials that went to the target from those that went to the onset at the 30° target distance, we analyzed RTs only for 90° and 150° target-onset separation. Trials in which angular deviation from the target was smaller than 20° (+ or −) were considered to be trials in which the eye went directly to the target. Note that we also calculated these RTs for the control condition. An ANOVA on mean RTs with SOA (control, 0, 90, and 150 ms) and distance as factors showed a main effect of SOA, $F(3, 21) = 5.0$, $p < .01$. Planned comparisons showed that the RT in the control condition was significantly faster than all SOAs ($ps < .05$), suggesting that even when the eyes went directly to the target, participants responded about 30 ms slower when an onset was present than when it was not (see Figure 7). There were no differences among the other levels of SOA ($ps > .20$).

Even though the eyes went directly to the target, there was

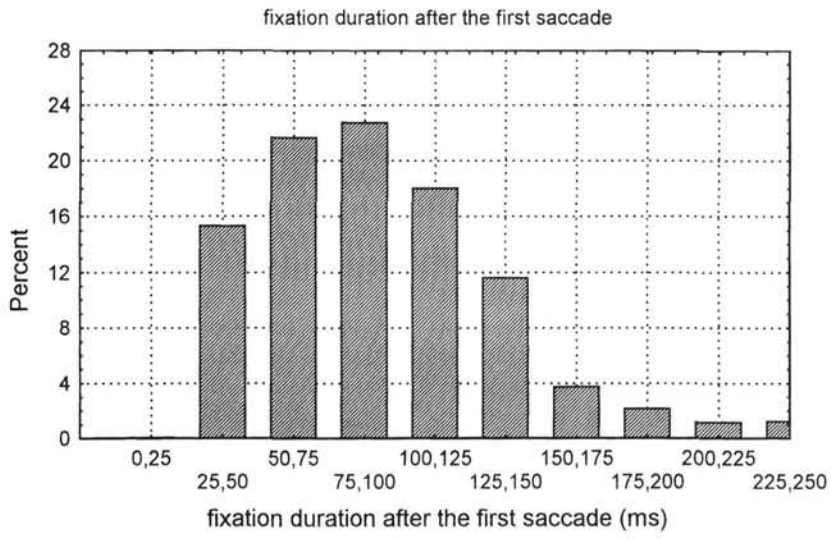

Figure 6. Fixation durations (in milliseconds) after the first saccade for those saccades that went in the direction of the onset. The results displayed here are from the conditions in which the abrupt onset appeared at 90° and 150° from the target and the eye started to move in the direction of the onset.

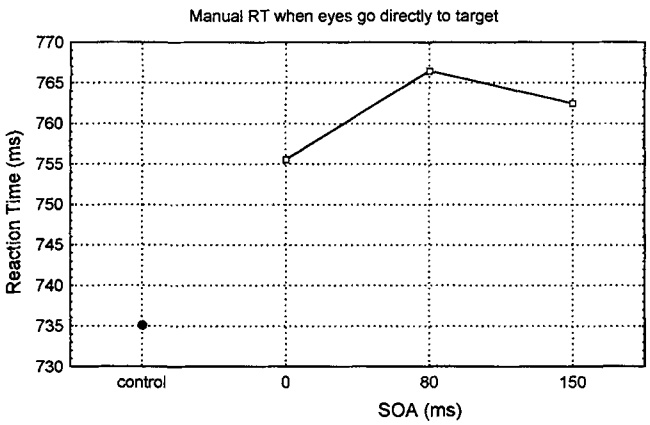

Figure 7. Manual mean reaction time (RT; in milliseconds) for those trials in which the eye went directly to the color singleton as a function of stimulus onset asynchrony (SOA).

still a reliable effect of the abrupt onset on manual RT. It was important for us to determine the cause of this effect. We analyzed the saccade latency for those trials in which the eyes went directly to the target (within a deviation range of −20° to 20°). The results indicate that there were no differences in saccade latency between the control condition (234 ms) and the other SOA conditions (237, 245, and 243 ms, respectively), Fs(1, 7) = 0.27, 2.9, and 2.7 for the 0-, 80-, and 150-SOA conditions, respectively, ps > .13, suggesting that the difference in manual RT (which was on average about 27 ms) could not be attributed to the fact that the eye started moving later in the onset conditions (which was on average about 8 ms).

We also calculated the time it took the eye to get near the target (within a 2° circle around the target). Again, there was no reliable difference between the control condition (294 ms) and the other SOA conditions (298, 310, and 311 ms, respectively), Fs(1, 7) = 0.35, 3.8, and 3.5 for the 0-, 80-, and 150-ms SOA conditions, respectively, ps > .09. Note that this measure (i.e., the time it took the eye to get near the target) also incorporated the small increases as found in saccade latency. Overall, these analyses indicated that the effect of the abrupt onset on manual RT for those trials in which the eyes went directly to the target occurred after the eye landed on the target.

RTs for trials in which the eyes went to the onset. Obviously, when the eyes move to the onset the manual RTs will be slow because, to give a manual response, the eyes need to be redirected from the onset to the target. Only for the 0-ms SOA (in which about 30%–40% of the trials the eyes moved in the direction of the onset) were there enough trials in the direction of the onset to acquire reliable and stable manual RTs. An analysis showed that for the 90° and 150° target–distractor separation the manual RTs were significantly longer than in the control condition (748 vs. 880 ms), $F(1, 7) = 52.9$, $p < .01$. There were no reliable differences between the 90° and 150° separation (877 vs. 883 ms) $F(1, 7) = 0.69$.

Discussion

The present results indicate that the planning and execution of a goal-directed eye movement toward a color singleton is disrupted by the appearance of an abrupt onset. In many instances the appearance of an abrupt onset caused the eye to start moving in the direction of the abrupt onset. Also, in cases in which the eye did not start to move in the direction of the onset, there was still a reliable effect on RT of the presence of the onset. Even though the abrupt onset was never task relevant, participants could not only not prevent attentional capture by the abrupt onset but, in many instances, they also could not prevent their eyes from moving to the onset.

Similar to Theeuwes (1995), who investigated the effect of attentional capture by an abrupt onset as a function of SOA, the disruption caused by the sudden appearance of the abrupt onset diminished when the onset was presented somewhat later in time than the color singleton. One reason for a smaller effect of the onset when it was presented later in time is that fewer saccades went in the direction of the onset (see Figure 4). In fact, there was no difference in the number of eye movements to the distractor between the 150-ms SOA and the control condition (see Figure 5), suggesting that at the 150-ms SOA the onset had no special status in the ability to elicit a saccade. The reason that the number of saccades toward the onset decreased as a function of SOA might be that when the onset appears later than the target, attention may be better focused on the color singleton, causing the programming of a saccade to that location to be farther away. Because the programming of a saccade to the target location is almost complete, the appearance of the onset at a longer SOA does not cause the eye to start moving in the direction of the onset. The finding that at the 150-ms SOA the onset does not affect the eye movement pattern is consistent with the model of Becker and Juergens (1979), who suggested that to modify the execution of a saccade, changes in target position must occur at least 80 ms before the onset of the saccade. Because the saccade latencies in our experiment were on average about 220 ms, an onset presented at the 150-ms SOA (i.e., 70 ms before the onset of the saccade) came too late to affect the eye movement pattern.

Note that even in the later SOA conditions in which the eyes went directly to the target, the abrupt onset still had an effect on the manual RTs (see Figure 7). This suggests that there might have been attentional capture (without an overt eye movement) after the eye landed on the target. In addition to these findings, the results indicating that there was an effect of the abrupt onset for those trials in which the eye went directly to the target (see Figure 7) also strongly suggest that the presence of an abrupt onset may slow down processing even when the eyes do not go to the onset. An important question is whether the onset does in fact capture spatial attention even when the eyes do not go to the onset. The effect of the onset on manual RTs for those trials in which the eyes went directly to the target may, for example, also be due to nonspatial distraction, that is, competition for attention between the target and the abrupt onset may cause

an RT increase without actually producing a shift in spatial attention (e.g., filtering costs; see Treisman et al., 1983). In Experiment 2 we addressed the question of whether the abrupt onset would cause capture of attention even for those trials in which the eyes did not go to the onset distractor. In other words, we addressed whether spatial attention ever shifted to the location of the abrupt onset for those trials in which the eye went directly to the target.

Experiment 2

To determine whether spatial attention ever shifted to the location of the abrupt onset, we used the response compatibility paradigm (B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1972), in which observers have to ignore a stimulus that is either compatible or incompatible with the response to the target. In previous studies (Theeuwes, 1996; Theeuwes & Burger, 1998) that investigated whether observers could intentionally ignore salient singleton elements, the element to ignore was either identical to or different from the target element they were looking for. The results showed that the identity of the element to ignore had an effect on RT, suggesting that spatial attention was directed at the location of the element to ignore. Participants were faster when the element to ignore was identical to the target (compatible with the response) than when the letter to ignore was different from the target (incompatible with the response).

To determine whether spatial attention was shifted to the location of the abrupt onset, we presented a large letter C or a large reversed C inside the abrupt-onset circle. This letter was either identical to the small letter inside the target color singleton (and therefore compatible with the response) or different from the small letter inside the target color singleton (and therefore incompatible with the response). The letter inside the onset was large enough that the identity of the letter could be determined without making an eye movement. In other words, the identity of the letter inside the onset could be determined by a covert shift of attention to the location of the onset.

In the current experiment, we used only the largest distance between the target and the onset (i.e., 150° of arc). This distance makes it clear which eye movements go to the target and which go to the onset. We used only the 0-ms SOA because this SOA gave the largest effects of the onset. Finally, instead of presenting control and experimental trials in separate blocks, we presented them in mixed blocks of trials.

Method

Participants. Sixteen participants (aged 18–30 years) participated as paid volunteers. All had self-reported normal or corrected-to-normal vision and reported having no color vision defects.

Stimuli. The letter located inside the circle presented with the abrupt onset was either a C or a reversed C. The letter located inside the onset was either the same as the letter in the target (both Cs or reversed Cs, response compatible) or different from the letter in the target (e.g., a C and a reversed C, response incompatible).

To ensure that the letter inside the abrupt onset circle could be perceived without making an eye movement[1] (i.e., could be perceived while fixating the center fixation dot), the viewing distance to the screen was increased to 80 cm and the letter inside the abrupt onset circle was increased in size to 1.1 × 0.5 cm. Because of these changes the circles had a diameter of 2.6° and were presented on an imaginary circle with a radius of 8.6°. The large letters were 0.8° × 0.4° in size and the small letters 0.28° × 0.14°. To ensure that the circle presented with the abrupt onset was not the only circle that had a large letter inside, half the distractor letters inside the other circles were large letters and the other half were small. These distractor letters were taken from the set S, H, E, P, F, and U. The position of the large and small letters located in the circles was randomized. Note, however, that the letter inside the gray target circle was always small (ensuring that participants had to make an eye movement) and the letter inside the abrupt onset was always large.

Procedure. Unlike in Experiment 1, trials with an abrupt onset and trials without an onset were presented in the same block of trials. Also, in this experiment only a 0-ms SOA was used, and if the abrupt onset was present it was presented at 150° away from the target. Participants performed 64 practice and 256 experimental trials. On half the trials, simultaneously with revealing the target color singleton a circle with an abrupt onset was presented 150° from the target. In the other half of the trials (the control condition), no additional circle was present. When an abrupt onset was presented, in half the trials the letter located inside the abrupt onset was compatible with the response to the target letter; in the other half of the trials it was incompatible with the response to the target.

Results

Discarded data. In the current experiment only 1% of the trials were discarded because of technical problems. In 10.8% of the trials, participants made anticipatory eye movements, indicating that they were not well fixated at the center fixation dot at the beginning of the trial. In 1.8% of the trials, participants made errors (pressing the wrong response key). Again, because error scores were so low, we did not analyze them further.

Manual RT. Participants responded significantly slower in the condition in which an onset was present (mean RT = 969 ms) than in the control condition (mean RT = 894 ms) in which no onset was present, $F(1, 15) = 26.8, p < .01$. In the condition in which there was an onset, the identity of the large letter inside the onset did affect RT. Participants were significantly faster, $F(1, 15) = 24.6, p < .01$, when the large onset letter was compatible with the response to the target (mean RT = 954 ms) than when the large onset letter was incompatible with the response (mean RT = 983 ms) to the target.

Scan path. Figure 8 shows the angular deviation from a linear path between the fixation dot and the target. As is clear from Figure 8, when an onset was present (lower panel) the eyes started moving in the direction of the onset on 36% of the trials. In the control condition, the eyes generally went directly in the direction of the target.

[1] Two trained observers were able to determine the identity of the large letter C or reversed C without moving their eyes at the eccentricity and visual angles tested in this experiment.

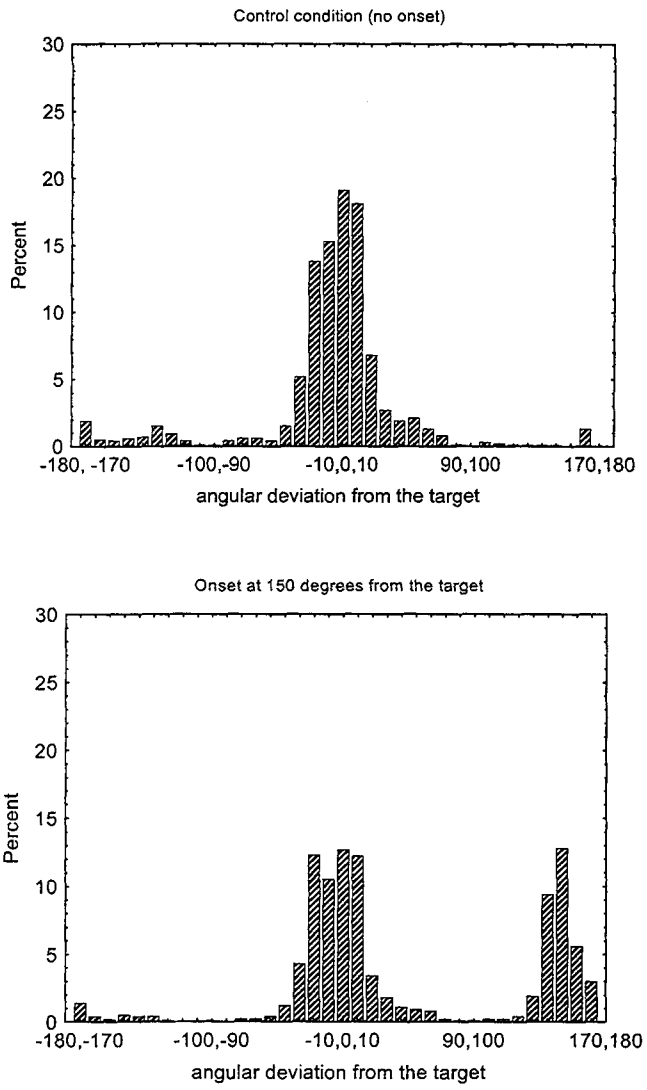

Figure 8. The effect of the appearance of the abrupt onset on the scan patch of the eye in Experiment 2. Shown is the maximum angle deviation of the eye from a linear path between the fixation and the target object (in degrees of angle; positive values indicate that the eye moved in the direction of the onset; negative values indicate that the eye went in the opposite direction). Sample points were taken only from the first saccade.

Saccade latencies for saccades toward and away from the target. In the condition in which an onset was present and the eyes went directly to the target (±10° angular deviation from the target) saccade latency was significantly longer (mean saccade latency = 314 ms) than when the eyes first went to the onset (mean saccade latency = 244 ms), $F(1, 15) = 23.4, p < .01$.

Fixation durations after the first saccade. We analyzed the fixation durations after the first saccade for those saccades that went in the direction of the onset (see Figure 9). As in Experiment 1 the majority of fixation durations (about 80%) were less than 150 ms, even though in this experiment (which used only the 150° target–distractor separation) a complete reversal of the eye movement was necessary to redirect the eye to the direction of the target.

Compatibility effect for saccades that went directly to the target. We analyzed whether the compatibility of the large letter inside the onset had an effect even when the eyes went directly to the target (±10° angular deviation). The results indicate a compatibility effect of about 30 ms (893 ms when the letter was compatible vs. 923 ms when the letter was incompatible), suggesting that participants were faster when the letter was compatible than when it was incompatible with the target, $F(1, 15) = 11.3, p < .01$.

Discussion

The results of Experiment 2 replicate all main findings of Experiment 1: Manual RT was slower when an onset was present than when it was not. The angular deviation measure showed that in many cases (about 36%), the eyes initially went in the direction of the onset. Fixation durations after the first saccade for those saccades that went to the direction of the onset were relatively short (80% shorter than 150 ms). Finally, saccade latencies were significantly shorter when the eye went to the onset than when the eye went to the target.

In addition to this replication of the basic findings of Experiment 1, the significant compatibility effect of 30 ms for those trials that went directly to the target suggests that spatial attention was indeed at the location of the onset even when the eye never went to the onset. Because trials in which the letter inside the onset was compatible with the target were faster than trials in which it was incompatible with the target suggests that at some point before giving a manual response, spatial attention was shifted to the location of the onset. Note that the size of the effect (about 30 ms) was comparable to the effect size in an earlier study (Theeuwes, 1996). Theeuwes (1996) reported a compatibility effect of 39 ms (Experiment 2), which could have been due to an attentional shift to the distractor because the display was presented for only 200 ms, a duration too short to make directed eye movements. Given the fact that the

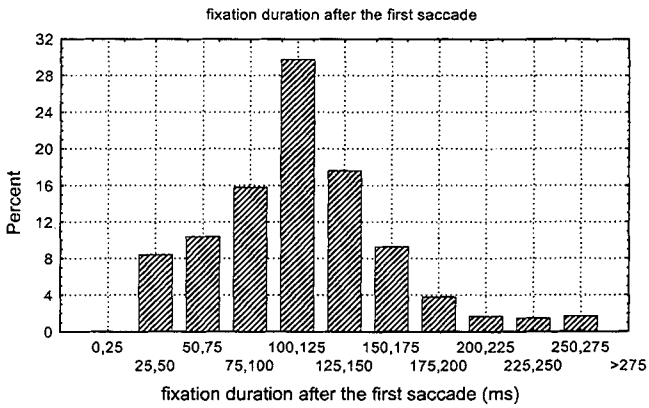

Figure 9. Fixation durations (in milliseconds) after the first saccade for those saccades that went in the direction of the abrupt onset.

effect sizes were comparable to those reported by Theeuwes (1996), in which it was impossible to make eye movements to the distractor, it is likely that indeed in the current experiment the abrupt onset captured attention even though the eyes never went in the direction of the distractor.

General Discussion

The present findings indicate that abrupt onsets capture attention in an involuntary, stimulus-driven manner. In addition, the capture of attention to the location of the onset resulted in the movement of the eyes, in about one third of the trials, toward the task-irrelevant onset distractor. Even though observers had an attentional set to search for a color singleton, top-down attentional set did not prevent attentional capture by the abrupt onset. These findings are consistent with those of Theeuwes (1994b, 1995), who showed that a top-down attentional set toward a color singleton could not overcome attentional capture by an abrupt onset.

The current findings that the top-down attentional set could not overcome attentional capture by the onset is not consistent with the contingent capture hypothesis suggested by Folk et al. (1992), who claimed that the control of attention is never purely stimulus driven. According to this hypothesis, orienting to a stimulus is contingent on the attentional set of the observer. If, as in our experiments, an observer has an attentional set to search for a color singleton, observers should be able to simply ignore an abrupt onset. The results clearly show that observers were unable to ignore the abrupt onset: Besides attentional capture, the onset caused the eyes of the observer to start moving in the direction of the onset.

It is important to develop a model that can explain the majority of the current findings. Before describing this model, we summarize the most important findings that the model must be able to accommodate. The most important findings are as follows: (a) short fixation durations after the first saccade for those saccades that went to the onset; (b) shorter saccade latencies for saccades that went initially to the onset than for saccades that went to the target; (c) an effect of the onset on RTs even for those saccades that went directly to the target; (d) an effect of the onset on manual RTs at the later SOAs; (e) when the eye went directly to the target there were no differences in saccade latencies between the control and the experimental conditions; and (f) when the eye went directly to the target, at some point before a response was given, there was a shift of spatial attention to the location of the onset.

The model incorporates various assumptions: (a) We assume that participants have the goal to make an eye movement toward the color singleton. To make this goal-directed eye movement, the singleton has to be first detected and attention needs to be shifted to the location of the color singleton. Then, to identify the target inside the singleton a saccade must be programmed to that location. We assume that the process of detecting the singleton, shifting attention to the location, and programming a saccade runs off in a more or less undisturbed, all-or-none fashion. (b) At the same time, in parallel, while preparing this goal-directed eye movement, attention is reflexively drawn to the location of the onset. We assume that the reflexive shift of attention to the onset initiates the programming of a reflexive saccade to the location of the onset. Again, the capture of attention and the subsequent preparation of the saccade to the onset is also assumed to run off more or less undisturbed. (c) If attentional capture by the onset occurs early in time (at a 0-ms SOA), programming of the reflexive saccade will finish before the planned eye movement toward the color singleton is ready; in this case, the eyes will start moving in the direction of the onset. As soon as the eye movement toward the color singleton is ready, the reflexive saccade toward the onset will be inhibited. This inhibition will cause the eye to stop at the location of the onset for a brief fixation before the goal-directed saccade is executed toward the color singleton. (d) If attention is captured by the onset somewhat later in time, programming of the voluntary saccade will finish before programming of the reflexive saccade and a saccade will be executed toward the target.[2] On landing on the target, attention (not a saccade) will be shifted exogenously to the location of the onset before a response is made.

The model just described provides a reasonable account of the oculomotor and performance data obtained in our studies. (a) Fixation durations are brief after the first saccade for those saccades that went to the onset because there is parallel programming of two eye movement programs (see Becker & Juergens, 1979; Henderson & Ferreira, 1990; McPeek, Skavenski, & Nakayama, 1996; Morrison, 1984). As soon as inhibition is applied to the reflexive eye movement, the eye movement program toward the color singleton is loaded and an eye movement to the target is initiated after a brief fixation. The saccade is redirected to the location of the target. This idea fits well with the finding that some components of the oculomotor system (e.g., the supplementary eye fields) are capable of programming and directing saccades within craniotopic coordinates (i.e., a coordinate system in which target location is determined with respect to the position of the head and therefore the eye is programmed to reach a specific point in orbit) and therefore would not require the saccade to the target to be reprogrammed after the eyes land near the onset (Mays & Sparks, 1980; Pierrot-Deseilligny, Rivaud, Gaymard, Muri, & Vermersch, 1995; Zee et al., 1976). (b) Saccades that went to the onset have a shorter latency than saccades that went to the target because the reflexive eye movement toward the onset is the result of the capture of attention by the onset before the voluntary saccade to the target is ready. Only if attention happens to be captured early in time will a reflexive eye movement be executed. (c) An effect of the onset on RT

[2] We assume that the programming of both reflexive and goal-directed saccades as well as the generation of attentional interrupts that results in the capture of (covert) attention (Martin-Emerson & Kramer, 1997; Yantis & Jonides, 1984) are stochastic processes. Therefore, even when a task-irrelevant onset occurs simultaneously with the color change that defines the target, misfixations on the onset will occur only on a limited number of trials.

even for those trials in which saccades went directly to the target is caused by the fact that attention is captured by the onset after the eye landed on the color singleton. It is feasible that as soon as the abrupt onset is presented it receives a temporary tag (e.g., Yantis & Jones, 1991). After the execution of the saccade to the location of the color singleton, the temporary tag at the location of the onset has not decayed, causing attentional capture to the location of the onset. (d) An effect of the onset on manual RTs for later SOAs is due to attentional capture to the location of the onset after the eye has landed on the color singleton. (e) The finding that there were no differences in saccade latencies between the control and the experimental conditions when the eye went directly to the target suggests that the planning and execution of a saccade runs off in a more or less undisturbed fashion. When the eye went to the target, the effect of the onset causing capture of attention showed up only after the eye had landed on the target. Attention may shift later to the location of the color singleton because its location is temporarily tagged. (f) The compatibility effect showed up for trials in which the eye went to the target because attention was shifted to the location of the onset after the eye landed on the color singleton.

The model fits well with recent neurophysiological evidence that suggests that different neuroanatomic structures are responsible for voluntary (goal-directed) and reflexive (stimulus-driven) saccades (Maunsell, 1995; Schall, 1995). In line with the claims regarding the parallel programming of two saccades, there is evidence that there are two pathways involved in the generation of saccades: the parietal eye field–colliculus pathway and the frontal pathway, which consist of the frontal eye fields, supplementary eye fields, and the dorsolateral prefrontal cortex (Henik, Rafal, & Rhodes, 1994; Schall, 1995; Pierrot-Deseilligny et al., 1995; Schall & Hanes, 1993). Generating goal-directed saccades toward the color singleton presumably depends on the frontal pathways, whereas the parietal–superior colliculus pathways are involved in producing the reflexive movements toward the abrupt onset. Research has shown that reflexive saccades generated by the superior colliculus can be inhibited through the substantia nigra from the frontal eye fields (Schall, 1995). Research has also shown that monkeys can still produce fast saccades to a flashed target after lesions of the frontal eye fields, but not after lesions of the superior colliculi (Schiller, Sandell, & Maunsell, 1987). Also, patients with lesions to components of the frontal pathways have difficulty producing goal-directed saccades in the direction opposite that of a flashed target (Guitton, Buchtel, & Douglas, 1985; Henik et al., 1994; Rivaud, Muri, Gaymard, Vermersch, & Pierrot-Deseilligny, 1994).

The model assumes that attention can be at two locations at the same time, allowing the programming of two eye movements in parallel. This assumption may be problematic given the claims that attention cannot be split between two locations (e.g., Posner, 1980). Recently, however, Kramer and Hahn (1995; Hahn & Kramer, 1998; see also LaBerge, 1995; Shaw & Shaw, 1977) have demonstrated that splitting attention between two locations is possible. If attention can be allocated to two locations at the same time, then it can be assumed that the results are due to a simple horse race between two eye movement programs. The one that is ready first will go in a winner-take-all fashion. If the program toward the onset is ready first, it will be executed. A reflexive eye movement will start until the goal-directed program to the color singleton is ready. When this program is ready, inhibition from the frontal eye fields on the superior colliculi will stop the eye movement toward the onset and after a brief fixation a saccade will be executed toward the color singleton. If the program toward the color singleton is ready first, it will be executed. On landing on the color singleton, attention will be shifted toward the onset because this location is tagged (or possibly attention is still residing at that location).

Alternatively, if attention allocation to two locations at the same time is impossible, it may be assumed that attention was sequentially shifted between the two locations during a critical time of the saccadic planning period. Because attention was at one or the other location during this critical period, two saccades may have been programmed in parallel to these different locations.

Kowler et al. (1995) also described these two alternatives. According to their spatial model, attention can be allocated at the same time to two locations during the entire saccadic latency period. According to their temporal model the end point of a saccade is determined by the locus of attention during a critical segment of the saccadic latency period. It appears that both alternatives are viable and not necessarily critical for the overall model described earlier.

As an alternative but highly similar notion, one could argue that endogenous and exogenous orienting occurs in parallel and that the programming of an eye movement to the onset has a head start because exogenous orienting is faster than endogenous orienting. Once attention is endogenously directed to the target, a saccade to the target is programmed. According to this line of reasoning, it is the differences in time course in exogenous and endogenous orienting that cause the eye to start moving in the direction of the onset rather than difference in programming reflexive and voluntary saccades.

Our results indicate that abrupt onsets may not only capture people's attention but that it may also capture their eyes. Such a mechanism is ecologically beneficial because abrupt onsets usually signify new objects that may be potentially important to the organism. Our research was an attempt to integrate attentional capture and oculomotor control in a model that is neurophysiologically plausible. Future research is necessary to determine whether the assumptions on which this model is based are accurate.

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Call for Nominations

The Publications and Communications Board has opened nominations for the editorships of ***Behavioral Neuroscience, JEP: Applied, JEP: General, Psychological Methods,*** and ***Neuropsychology*** for the years 2002–2007. Michela Gallagher, PhD; Raymond S. Nickerson, PhD; Nora S. Newcombe, PhD; Mark I. Appelbaum, PhD; and Laird S. Cermak, PhD, respectively, are the incumbent editors.

Candidates should be members of APA and should be available to start receiving manuscripts in early 2001 to prepare for issues published in 2002. Please note that the P&C Board encourages participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. Self-nominations are also encouraged.

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- Sara B. Kiesler, PhD, for ***JEP: General***
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